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Jonathan Roth  
*John Deere*

Matthew J. Darr  
*Iowa State University, darr@iastate.edu*

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# MEASUREMENT OF NORMAL STRESSES AT THE SOIL-TIRE INTERFACE

J. Roth, M. Darr

**ABSTRACT.** *Agricultural energy usage is an important topic among agricultural industry producers, manufacturers, and regulators. The transfer of power between axle and drawbar is identified as one of the greatest inefficiencies in agricultural field operations. Understanding the stresses at the soil-tire interface would provide insight into the current state of tire traction development and data useful in developing future tire designs. This article presents a measurement system to quantify the normal stresses at the soil-tire interface of an agricultural tractor tire, thus making it possible to evaluate these stresses along the tire footprint. A normal stress measurement system was developed in the laboratory and tested in the field. Additionally, a dedicated data acquisition system was developed, tested, and validated in the field environment. Test results show the system capabilities as well as information on the challenges of drawing general, consistent conclusions concerning the stresses developed between a tire and the soil at field working speeds in agricultural soil.*

**Keywords.** *Sensors, Soil-tire interface, Tires, Traction.*

Modern farming techniques make heavy use of tires as tractive devices for nearly every field operation. As a mechanical device, the traditional lugged agricultural tire is rather inefficient at converting the torque and speed at a tractor axle into force and linear motion at the drawbar. Zoz and Grisso (2003) stated that the soil-tire interface has been shown to have inefficiencies on the order of 20% to 55%. Over the last 25 years, an increased focus on soil compaction has also renewed interest in the tractive efficiency of the tire. Despite advances made throughout that time, there is still an opportunity to improve the efficiency of the modern agricultural tire. To take advantage of this opportunity, more data are required to understand the current method of traction generation to allow better decisions to be made during the tire development and design phases.

The contact area of a tire represents the interface region developed when a tire comes in contact with the ground. This region is critical for the development of traction, as it controls the transfer of forces between the tire and the ground (Wulfsohn, 2009a). Although estimation methods are available to predict the contact area of agricultural tires, the determination of the true 3-D contact area in real-time is difficult and relies on accurate methods of measuring tire deflection (Koolen and Kuipers, 1989). Direct measurement of soil-tire interface stresses can greatly improve es-

timations of contact area and lead to improved understanding of the soil-tire dynamics that exist within high-load agricultural applications (Wulfsohn, 2009a). While summarizing the state-of-the-art in soil-tire interface stress measurement, Wulfsohn (2009b) concluded that direct measurement of interface stresses enables prediction of pressures along the soil surface and the overall tractive performance of the tire. Additionally, it was noted that direct measurement of stresses on the tire was preferred over strain measurements from within the soil due to difficulty with in-field instrumentation and repeatability of the measurement technique.

The first work measuring stresses normal to tire faces in lugged tires was performed by Trabbic et al. (1959). Strain gauge based pressure transducer cells were developed and inserted into a lugged 13.6-38, 4-ply bias agriculture tire. Two opposing lugs (one on either side of the tire centerline) were instrumented with five cells each on the leading and trailing lug faces, as well as five cells each in the outer lug face and the tire undertread (space between lugs), for a total of 40 pressure cells. The results showed large variations in pressure across the lug for all cell locations (undertread, leading, outer, and trailing lug faces), at all inflation pressures, and at various drawbar loads. The investigators also noted the significance of slip compressing soil into the tire undertread regions.

More recent work in tire interface pressures focused on the changes in interface pressures as the production agriculture industry shifted from bias to radial-ply tires and from higher to lower inflation pressures in the 1990s. A study of the effects of inflation pressures and dynamic load on soil-tire interface pressures was conducted at the National Soil Dynamics Laboratory (NSDL) in 1994 (Raper et al., 1995a, 1995b). Seven pressure cells were mounted in an 18.4R38 Goodyear R-1 tractor tire (four in the lug face, three in the undertread). Dynamic load, inflation pressure, slip, and

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The authors are **Jonathan Roth, ASABE Member**, Engineer, John Deere Product Engineering Center, Waterloo, Iowa, and **Matthew Darr, ASABE Member**, Assistant Professor, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa. **Corresponding author:** Matthew Darr, Department of Agricultural and Biosystems Engineering, Iowa State University, 100 Davidson Hall, Ames, IA 50011; phone: 515-294-8545; e-mail: darr@iastate.edu.

axle torque could be controlled in the soil bin tests conducted in loose sandy loam and loose clay loam. Reductions in inflation pressure caused soil-tire interface pressures to decrease at the centerline but not the edge of the tire. This shows the influence of sidewall strength on pressure distribution. At constant dynamic weight, the normal stress at the tire edge did not increase as inflation pressure decreased. Rather, the weight not supported by the tire center was countered by a longer tire footprint. It was also found that inflation pressure usually significantly affected the pressure at the lug-tire center position, while dynamic load effects were most significant at the lug-tire edge position and undertread area.

A similar study was presented by Way and Kishimoto (2004). An 18.4R38 Armstrong R-1 radial tire was instrumented with six of the same pressure cells as in the NSDL test (Raper et al., 1995a, 1995b). In this study, the tire was operated in soil bins containing loose sandy loam, loose clay loam, and structured clay-type soil. The main objective was gathering data to compare the differences in soil-tire interface pressures among differing soil types. Way and Kishimoto (2004) found that although the lug penetrated in the structured clay loam soil, the interface pressure in the undertread area was significantly lower than the inflation pressure (as low as 0.17 times the inflation pressure), while pressures in the lug areas ranged as high as 5.98 times the inflation pressure. In the loose sandy and loose clay loam soils, soil-tire interaction pressures (normal stress) ranged from 0.84 to 1.37 and from 0.18 to 1.71 times the inflation pressure, respectively. Variability in measurements among several tire revolutions was not discussed by Way and Kishimoto (2004).

Misiewicz et al. (2008) reported a different approach to finding interface pressures. Using a piezoelectric mat between the tire and the traction surface of interest, a true snapshot of the pressure distribution can be found. Although the presented data only represented the interaction between a ribbed tire and a solid surface, suggested future work included analyzing the soil-tire interface using this sensing method.

## OBJECTIVES

This study's long-term research goal was to increase the tractive efficiency of agricultural tires. There has been much research in modeling the tire to characterize the relationship between the input (axle torque) and output (drawbar pull) of the system, but issues in understanding the true soil-tire interaction still exist. The specific objective of this study was to develop and field test a system to measure the normal stress at the soil-tire interface.

## MATERIALS AND METHODS

### SENSOR SELECTION

FlexiForce piezoresistive normal pressure sensors were used to measure stresses at the lug leading and trailing sides and the undertread area (Tekscan, Inc., South Boston, Mass.). These sensors are thin and flexible with a relatively small sensing area (9.5 mm dia.), allowing a high placement density in the areas to be measured. Based on data

from previous studies, the sensor selected was rated at a 111 N load over the 71 mm<sup>2</sup> sensing area.

The sensor converted an applied normal load into a non-linear resistance between two leads. Although the resistance ( $R$ ) was non-linear, the conductance ( $R^{-1}$ ) was linear in relation to the applied load. Each sensor was unique in terms of the relationship between applied load and output conductance. A conditioning circuit suggested by the manufacturer was modified for use in this application to provide a 1.25 to 5 V signal linear to the applied load. Although each sensor calibration was unique, the same conditioning circuit was used for all sensors.

### SENSOR PLACEMENT

Work by Trabbic et al. (1959) suggested that at least five sensors across the lug face are required to determine the soil-tire interface characteristics. For this study, five FlexiForce sensors were located across the half the width of the tire at the lug leading and trailing sides and in the undertread trailing and leading areas (fig. 1). The leading lug sides and undertread areas are the first to impact the soil when the tractor is moving in a forward direction.

The FlexiForce sensors were mounted to a small circular steel plate backing (3.2 mm thick, 23.8 mm dia.) before installation on the tire. This provided a solid base, as well as prevented significant deflection at the sensor face. The circular metal plate backing was in turn attached with epoxy to the tire in the indicated location (fig. 1). The plate moved with the rubber, allowing the usual tire flex while keeping the sensor face from flexing. The plate was similar in size to the solid metal transducers used by Way and Kishimoto (2004) and Raper et al. (1995a, 1995b).

### DATA ACQUISITION

A custom data acquisition (DAQ) unit was developed to gather data from the sensors. The DAQ unit was mounted directly to the wheel and logged normal stress data to a

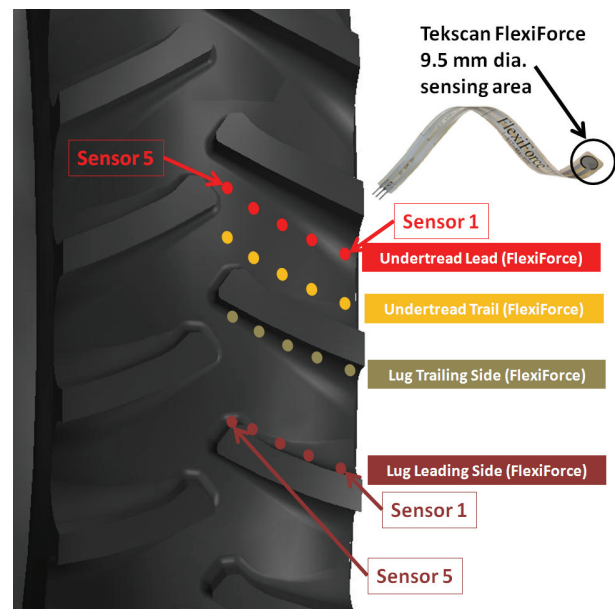


Figure 1. Location of normal stress sensors at the leading and trailing sides of the lug and undertread.

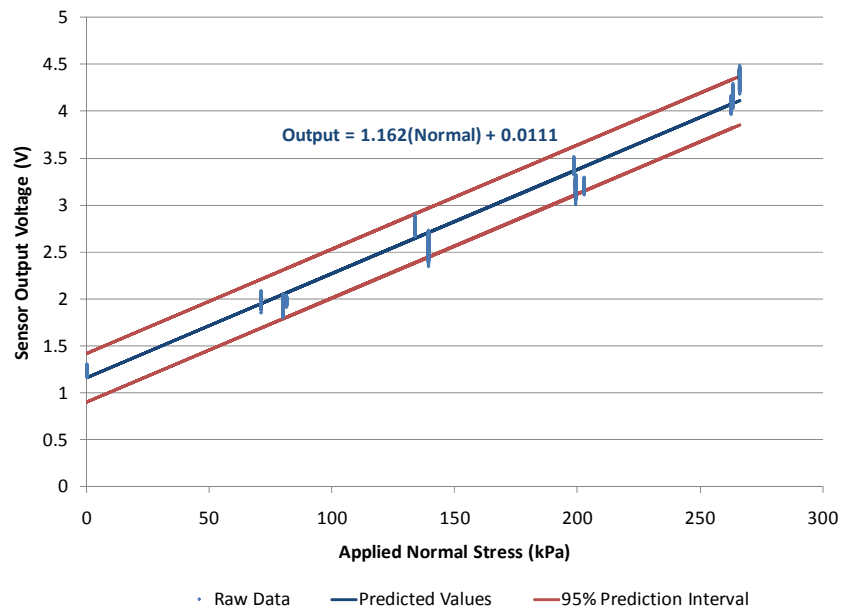


Figure 2. Piezoresistive sensor response to applied pressure.  $R^2 = 0.9832$  for the indicated linear calibration curve.

removable compact flash card. A two-axis accelerometer was also mounted to the axle and used to determine the wheel angular rotation and the sensor position relative to the soil during data acquisition. Before analysis, an angular offset was applied to the data from each sensor to resolve its absolute location.

#### FLEXIFORCE SENSOR ON-TIRE ANALYSIS AND CALIBRATION METHODS

On-tire calibration confirmed proper operation of each sensor and the associated conditioning circuitry. Additionally, the results provided data for an accuracy assessment of the final calibration equations for each sensor.

Each sensor was calibrated individually using pressurized air. A compressed air load was applied to each sensor in three sets of five different pressure levels, ranging from 0 to 276 kPa, in intervals of 69 kPa. The order of the applied pressures within each set was chosen randomly, resulting in 15 observed calibration points (three of each pressure level) for each sensor. During calibration, the applied compressed air load was allowed to reach steady state. The sensor output was then oversampled at a rate of 833 Hz until a total of 1584 data points were recorded. The oversampled data points were averaged to yield a single calibration point. After each unique observation was recorded, the compressed air load was completely removed from the sensor before the next randomly selected calibration load was applied. This procedure ensured that each of the 15 observed calibration points was independent. The field data acquisition system was used during this data collection to eliminate any biasing from the analog inputs.

#### FLEXIFORCE ON-TIRE CALIBRATION RESULTS

Single-variable linear regression statistical analyses were used to evaluate the results from the calibration process. Variation in output voltage was considered as a function of applied pressure. Figure 2 shows the results from this process from the calibration of one sensor. The regres-

sion equations relating voltage to applied pressure were used to determine the calibration equation for each sensor. All sensors showed acceptable linearity and sensitivity.

#### FIELD TEST TRACTOR SETUP

FlexiForce sensors were attached to the right rear (operator's perspective) outside (dual) wheel of a John Deere 7930 IVT tractor (fig. 3). The tire used was a Firestone Radial All-Traction 23° of size 480/80R46 (Firestone Agricultural Tire Division, Des Moines, Iowa).

The instrumented tire operated outside the track of the front tire. This prevented any interaction between the compaction from the front tire and the traction from the rear. Figure 4 shows the field test tractor configuration. For testing, the tractor mass was unchanged from the factory ballasting (minus inside wheels) at 9540 kg total, with 6600 kg centered over the rear axle. Rear tire pressure was set at 138 kPa. No horizontal load was added, and the tractor was operated at 5.6 km h<sup>-1</sup>. The mechanical front wheel drive was disengaged for all tests.

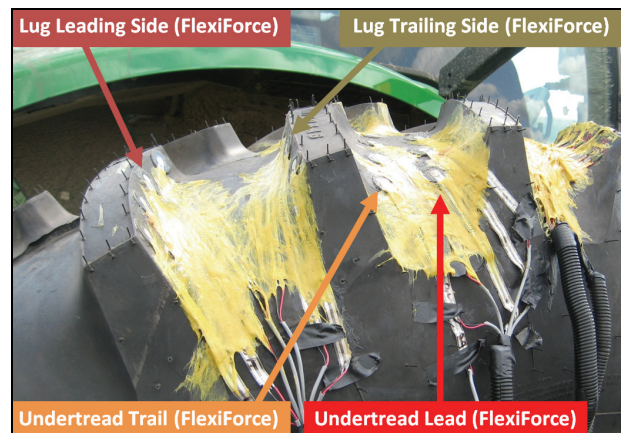


Figure 3. FlexiForce sensors installed on right outside tire of John Deere 7930 tractor.





Figure 4. John Deere 7930 IVT with inner rear wheels removed for testing purposes. Includes instrumented outside right rear wheel.

#### FIELD PREPARATION

All testing was conducted at the Iowa State University Agricultural Engineering and Agronomy farm on a loamy Orthents soil type (44% sand, 34% silt, and 22% clay). Pri-

or to testing, the field was in fallow grassland for six months. Three weeks prior to testing, the field was mold-board plowed at a depth of 20 cm. Following the plowing, but preceding testing by 2 h, three passes were made over the field using a field cultivator at a depth of 10 cm (fig. 5).



Figure 5. Soil conditions during testing.

## RESULTS

#### NORMAL STRESS DATA BLOCKING

Although the overall trends in the raw data were as expected based on previous studies, the raw data showed some noise in the angular position (fig. 6). Because angular position was determined directly from an accelerometer attached to the wheel, some noise was expected from vertical wheel movement and soil-tire interaction disturbances.

Blocking and averaging the data into two-degree intervals (fig. 6) yielded data similar in overall result but in smaller angular displacement intervals than data from previous studies, particularly that shown by Way and Kishimoto (2004). Data points within each blocked angular interval were analyzed to determine a 95% confidence interval on the mean of the normal interface stress within that interval. These confidence intervals were subject to influence by the general slope of the normal stress data over each two-degree interval, particularly at the engagement and disengagement regions of the curve (approximately  $-28^\circ$  and  $-6^\circ$  in fig. 6, respectively) where there were high rates of slope. A very high slope in the observed data over an interval would in-

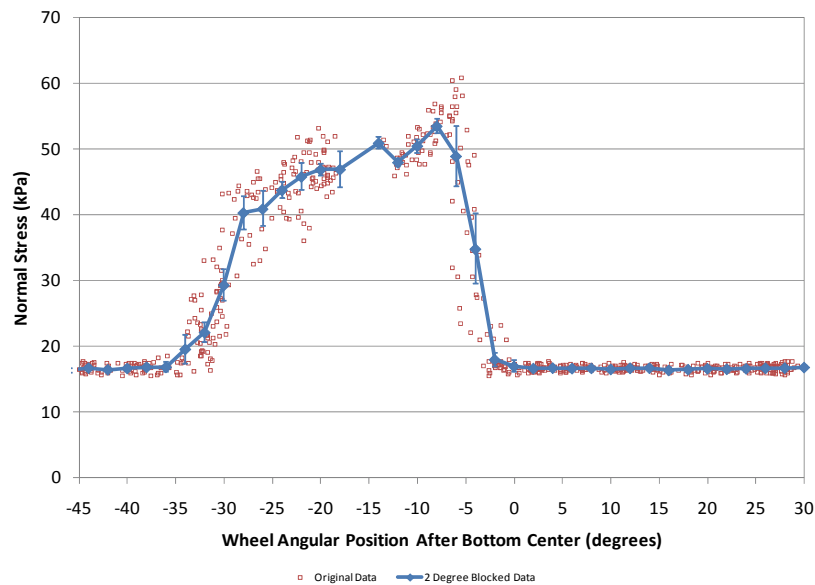


Figure 6. Testing run 2, revolution 8, undertread lead sensor 1 blocked data output by wheel angular position. Vertical lines indicate 95% confidence intervals for the means of the blocked regions.

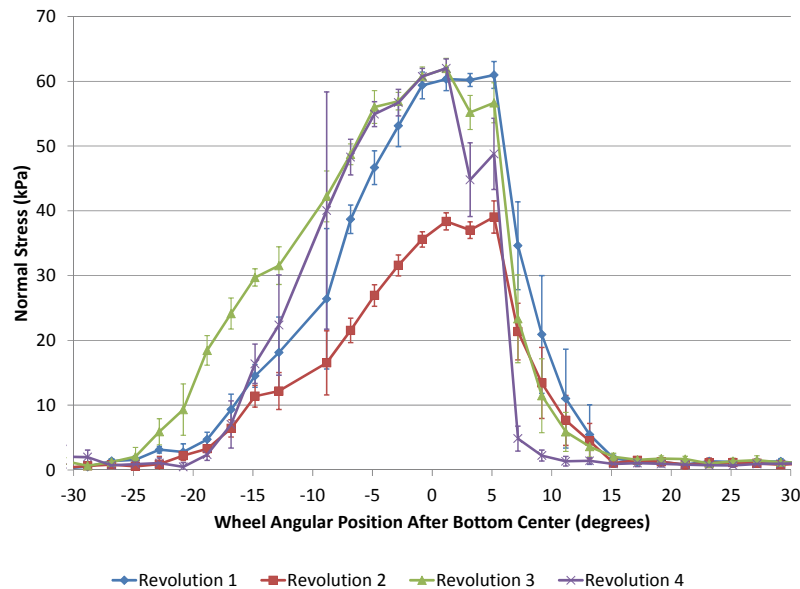


Figure 7. Testing run 2, revolutions 1-4, trailing side 1 sensor blocked output with 95% confidence intervals on each two-degree data block.

crease the standard deviation over the interval, biasing the confidence interval higher than it actually was at that angular position. This influence was minimized by decreasing the size of the blocking intervals from previous studies. This interval was also used to determine significant differences among different revolutions of the same sensor.

#### NORMAL STRESS VARIATION BY REVOLUTION

Normal stress data were recorded every time the sensors impacted the soil. Data were recorded over four tire revolutions, resulting in four sensor-soil interaction curves for each sensor. Normal stress measurements from the same sensor over several tire revolutions varied based on the sensor location and the revolution under consideration. Overall, similar normal stress curves for a given sensor generally occurred at contiguous revolutions (i.e., revolutions 3 and 4), while dissimilar data trends and magnitudes

generally resulted from discontinuous revolutions (i.e., revolutions 1 and 4). This was assumed to be due to soil conditions changing as the tractor moved along the field.

An illustration of similar data on a single sensor location over several tire revolutions (and sensor-soil interactions) occurred at the lug trailing side 1 sensor location on revolutions 1 through 4 (fig. 7). Tire revolutions 1, 3, and 4 showed very similar data in both magnitude and trend over the sensor engagement. Revolution 2 also showed a similar trend, although with a smaller magnitude. Overall, these data show similar responses to those seen in previous studies. However, there is an element of variability shown in these four revolutions that was not previously reflected. To determine the degree of this variability, 95% confidence intervals for the mean of each two-degree blocked data point were determined and are indicated in figure 7. These intervals help show the degree of magnitude variability in

**Table 1. Results from a two-sample t-test ( $\alpha = 0.05$ ) showing statistically significant differences among observed normal stress means over different revolutions for run 2, revolutions 1-4, trailing side 1 location, as shown in figure 7. The same letter in two separate columns indicates statistically similar means for two different revolutions for the given angular displacement.**

Angle (degrees)	Revolution Number			
	1	2	3	4
-28.8	A	A	A	A
-26.8	A	A	A	A
-24.8	A	A	A	A
-22.8	A	B	A	B
-20.8	A	A	C	B
-18.8	A	A	C	A
-16.8	A	A	C	A
-14.8	A	A B	C	B
-12.8	A	A	B	A B
-8.8	A B	A	C	B C
-6.8	A	B	C	C
-4.8	A	B	C	C
-2.8	A	B	B	B
-0.8	A	B	B	B
1.2	A	B	B	B
3.2	A	B	C	D
5.2	A	B	A C	C
7.2	A	B	A B	C
9.2	A	A	A	B
11.2	A	A	A	B
13.2	A	A	A	A
15.2	A	A	A	A
17.2	A	A	A	A
19.2	A	A	A	A
21.2	A	A	A	A

the data within that interval for the given revolution. Additionally, to statistically compare the revolutions shown in figure 7, the averaged data from each angular block from each revolution were compared using a two-sample t-test at 5% significance level ( $\alpha$ ). The results are shown in table 1. For each row of angular displacement in table 1 (i.e., row 1 at an angular displacement of  $-28.8^\circ$ ), the same letter in different revolution columns indicates that the mean normal stress for those revolutions at that displacement is statistically similar at the  $\alpha = 0.05$  level.

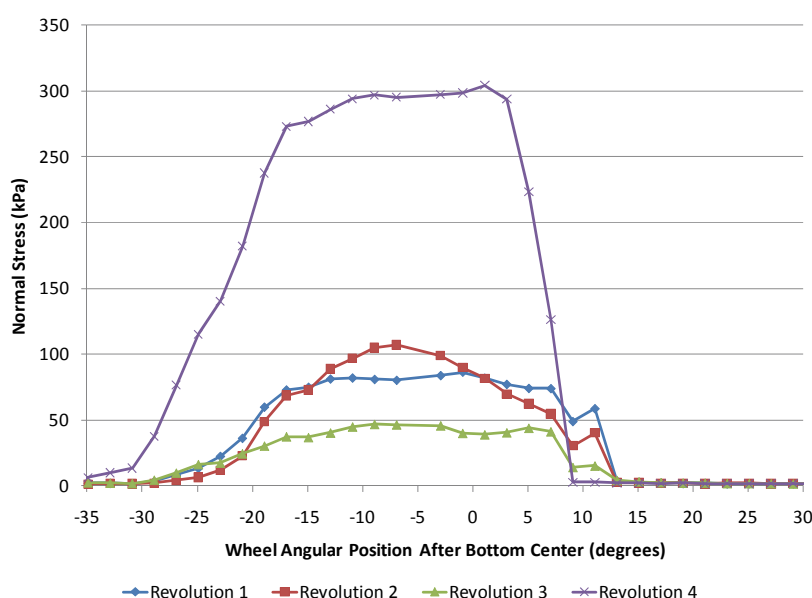
The similarity shown over four tire revolutions, which were spaced out over 17.5 m of tire travel, indicates the continuity that may occur at the soil-tire interface over several revolutions under similar soil conditions. However, even though the data in figure 7 show many similarities in trend over several revolutions, the curves were also significantly different at several different angular displacements. Revolution 2, in particular, has distinctively lower magnitudes of normal stress than either of the surrounding revolutions. Data from nearly all other sensors through the same tire revolutions also show significant dissimilarities. For example, the undertread trailing 3 and 5 sensor data were dissimilar in both overall trend and magnitude over revolutions 1 through 4 (figs. 8 and 9). In both figures 8 and 9, one revolution shows a much higher normal stress than the preceding revolution (revolution 4 in fig. 8) or both the preceding and following revolutions (revolution 3 in fig. 9).

Some consideration was given to calculating the mean normal stress curve over several revolutions for a given sensor location. However, because the data were frequently significantly different, it was not sound statistical practice to use these normal stress mean curves as a tool in comparing different sensor reactions.

The data were also analyzed for trends across the tire for each set of sensors (undertread leading, undertread trailing, lug leading side, lug trailing side). No dominant trend in the distribution of normal stress across the tire over several revolutions could be identified.

#### VARIABILITY IN CONSIDERATION OF FIELD CONDITIONS

Prior to testing, the field used was conditioned to a conventionally tilled seedbed environment. By nature, this environment includes several disturbances that may not be accounted for in the soil-bin testing presented in previous articles by Way and Kishimoto (2004) and Raper et al. (1995a, 1995b). In particular, the field included some soil particles larger than 20 mm in diameter and rocks larger



**Figure 8. Testing run 2, revolutions 1-4, undertread trailing 3 sensor location interface stresses blocked into two-degree intervals.**



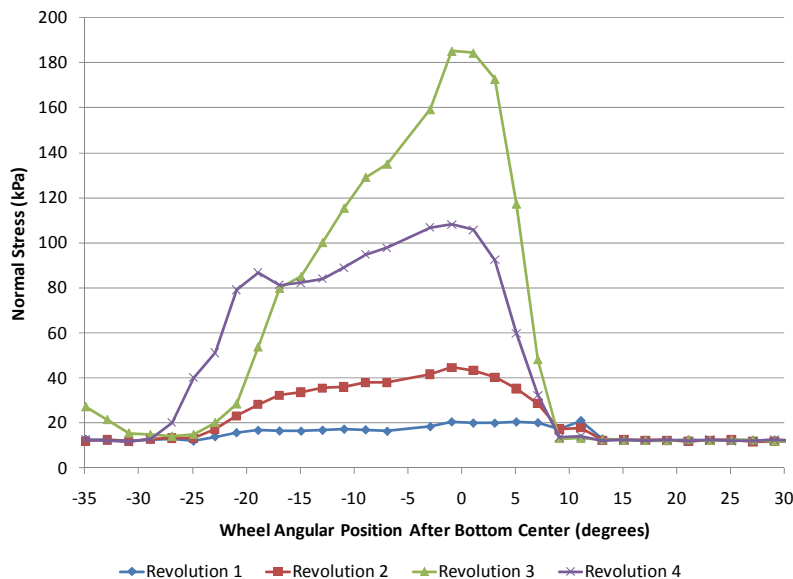


Figure 9. Testing run 2, revolutions 1-4, undertread trailing 5 sensor location interface stresses blocked into two-degree intervals.

than 40 mm in diameter. Although these disturbances may have led to increased variability in the resulting data, they are representative of a highly conditioned field environment. In fact, most Midwestern U.S. traction-intensive (primary and secondary tillage) operations require the tractor to operate in conditions with even more disturbances, such as crop residue and larger soil masses. The trend of significant differences among normal stress from the same tire locations over several revolutions shows the variability that can occur in the soil-tire interface in field conditions.

Another potential cause of the variability in interface stresses was the tire wheel speed. In previous studies, the tire under consideration was operated at wheel and travel speeds below  $0.6 \text{ km h}^{-1}$  (Way and Kishimoto, 2004; Raper et al., 1995a, 1995b). In those studies, speed was not considered a factor affecting the interface stresses. The data presented here were acquired at a field working speed of  $5.6 \text{ km h}^{-1}$ . This difference in speed, coupled with the soil surface variability, may account for the variability seen over several tire revolutions.

## CONCLUSIONS

Based on this study, in which we developed a piezoresistive-based normal stress sensor for soil-tire interface measurements, we found that:

- Two-degree blocking of dynamic soil-tire interface data provided a sufficient means to statistically compare individual sensors and evaluate variability across multiple replications.
- Normal stresses experienced at the soil-tire interface were highly variable under typical field conditions and at normal agricultural tractor working speeds.
- The level of dynamic variability measured at the soil-tire interface will inhibit direct measurement of stress as an input to a real-time traction control system.

## ACKNOWLEDGEMENTS

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